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Cryogenic disk Yb:YAG laser with 120-mJ energy at 500-Hz pulse repetition rate

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Abstract. **A repetitively pulsed laser system based on cryogenically cooled Yb:YAG disks is developed. The creation of Yb:YAG/YAG composites and the use of an active liquid nitrogen cooling system made it possible to significantly decrease the effect of amplified spontaneous emission. The average output power of the system is 60 W.**

Keywords: *pulsed laser, disk laser, Yb:YAG, cryogenic cooling.*

1. Introduction

Owing to efficient heat removal and weak self-focusing, active elements (AEs) in the form of thin disks are widely used for creation of lasers with high average and peak powers. In this lasers, the Yb^{3+} ion is used more and more frequently. This is related to a low quantum defect (~9%) and to the absence of absorption from the excited state [1,2]. For comparison, note that in AEs doped with Nd ions more than 30% of pump power is converted into heat [3] due to a high quantum defect and parasitic processes of up-conversion, cross-relaxation, and so on [4]. The low quantum defect of the Yb ion is caused by the small distance between the ground and the lower laser levels, because of which the population of the lower laser level at room temperature, according to the Boltzmann distribution, is 5%, and the system is only quasi-four-level. This problem is convenient to solve by cooling the AE to cryogenic temperatures (below 200 K), since this considerably increases the gain and absorption cross sections [5–7] and improves the thermo-optical constants of the medium [8–10].

Cryogenic disk lasers with a high average and peak power are being developed at the Institute of Applied Physics, Russian Academy of Sciences using all the advantages of Yb:YAG AEs cooled with liquid nitrogen. The long lifetime of the excited state of Yb:YAG (~ 1 ms) allows one to expect accumulation of a rather high energy in each individual pulse, and the good heat conduction (especially in the case of cooling) provides the possibility of operation with a high repetition rate. It is planned to create a laser system with a pulse energy of ~0.5 J and a pulse repetition rate of ~1 kHz (corresponding to the reciprocal lifetime in the medium). In this case, the cw pump energy is used most efficiently. Disk laser elements suffer weaker thermal distortions caused by longitudinal temperature gradient. In addition, the low thickness of AE considerably increases their breakdown threshold, which allows one to obtain ultrashort pulses (~100 ps) at a rather high pulse energy density.

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The first experimental results on this laser (100 mJ, 200 Hz) were published in [11]. To advance further, some steps were taken to modernise the system. A special diffusion bonding technology was developed to fabricate sandwich structures from a thin Yb:YAG disk and a thick YAG disk. The potentiality of such composite AEs is described in [12]. In comparison with ordinary disk AEs, the sandwich structures are characterised by considerably lower energy losses due to amplified spontaneous emission and by a higher parasitic oscillation threshold. In addition, these structures have a higher mechanical strength and better heat removal. It should be noted that a decrease in the amplified spontaneous emission leads not only to an increase in the stored energy but also to a decrease in the thermal load on the AE. However, heat release is still rather high, and, in the case of passive cooling, nitrogen begins to boil, which considerably reduces the heat removal rate. To solve this problem, an active liquid nitrogen cooling system was developed, which allowed one to considerably increase the laser pulse repetition rate.

In this work, we present the data obtained after a series of improvements of the system. In the first part, we describe the results on generation and amplification of radiation in a preamplifier cascade, and the second part is devoted to amplification in the main (output) cascade.

2. Master oscillator and preamplifier

The scheme of the cryogenic master oscillator system and the preamplifier (PA) is shown in Fig. 1. Two laser disks made of Yb:YAG crystals are placed at opposite sites inside a common cryogenic vacuum chamber. Each crystal from the side of the mirror is soldered with indium to a CuW heat sink cooled to liquid nitrogen temperature. The CuW alloy was chosen because its thermal expansion coefficient is close to that of YAG. To avoid frosting of the crystals, the pressure in the chamber was below 10^{-8} mbar.

The master oscillator (MO) included pump fibre-coupled laser diodes with a maximum power of 70 W and AEs 15 mm in diameter with different thicknesses and a doping level of 10 at%. We used a laser scheme with one V-shape pass and *Q*-switching by an acousto-optic modulator (AOM). With a 1.5-mm pump beam spot on the AE, we managed to obtain a high-quality output beam with an energy of 2 mJ in a 70-ns pulse at a pulse repetition rate of 1 kHz (Fig. 2). The output energy deviation was ~ 1% for two hours of operation. Figure 2 shows an increase in the slope efficiency from 7% to 14% with

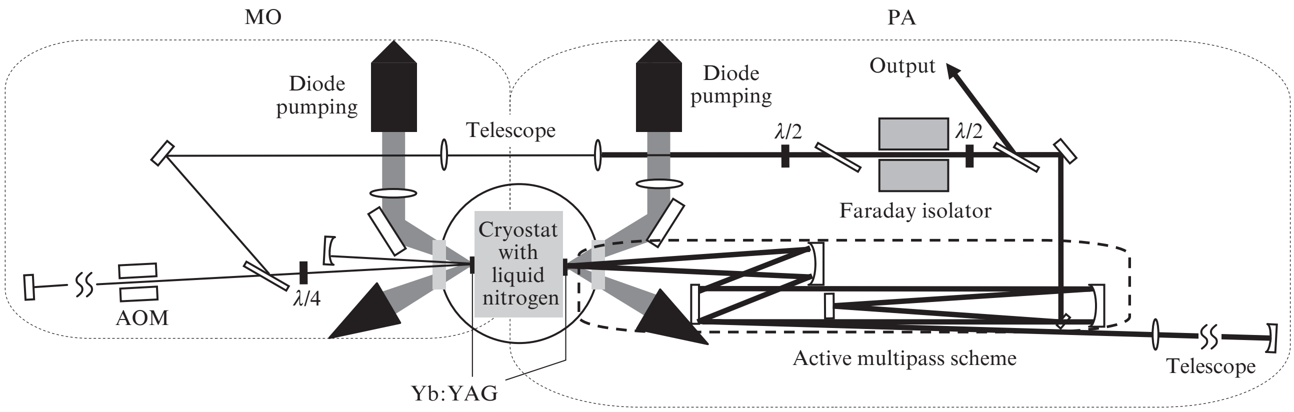

Figure 1. Principal scheme of the master oscillator and preamplifier.

replacement of a disk AE by a composite sandwich. Further increase in the output energy was limited by the breakdown of the AE and by the pump power. The slope efficiency can be increased by decreasing the reflection from the input window and replacing the available crystal with the excited-state lifetime of 500 μs by a crystal with a lifetime of 900 μs.

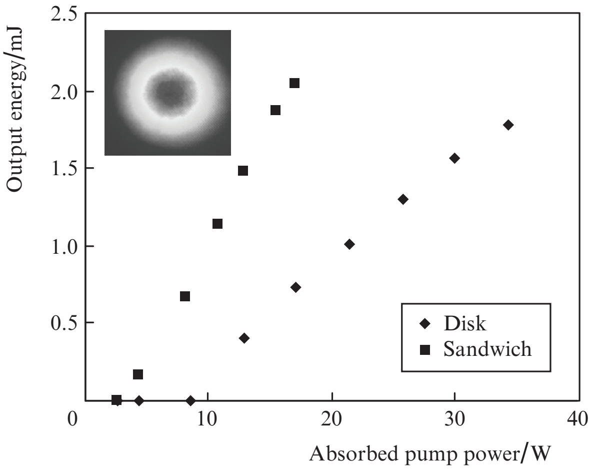

Figure 2. Dependence of the master oscillator output energy on the absorbed pump power in the case of the active element in the form of an Yb:YAG disk and an Yb:YAG/YAG sandwich.

The diameter of the beam emitted by the master oscillator was increased by a telescope to 3 mm, after which the beam propagated through a Faraday isolator made by us and entered the PA. One of the key factors limiting the PA frequency is the high heat release density, which leads to nitrogen boiling and sharply decreases the heat removal rate. To prevent these effects, we used a system of active liquid-nitrogen cooling.

The Yb:YAG disk was soldered to a heat sink, whose opposite side was immersed in a vessel with liquid nitrogen. At the same time, the AE itself was in a vacuum chamber with an input window for the pump and amplified beams. A cryogenic pump was immersed in the vessel with liquid nitrogen so that its outlet was directed to the heat sink. The advantages of the active cooling system compared to passive cooling are evident from the measurements of the small-signal gain and of phase distortions in an AE 900 μm in thickness and 15 mm in diameter with a pump spot diameter of 3.8 mm. The phase distortions measured using a Michelson interferometer at an absorbed pump power of 140 W are presented in Fig. 3a. It is seen that distortions in the case of passive cooling are caused both by thermal lens formation and by deformation of the disk as a whole, while deformations in the case of active cooling are absent and, hence, the average AE temperature is much lower. Another advantage of active cooling is clearly

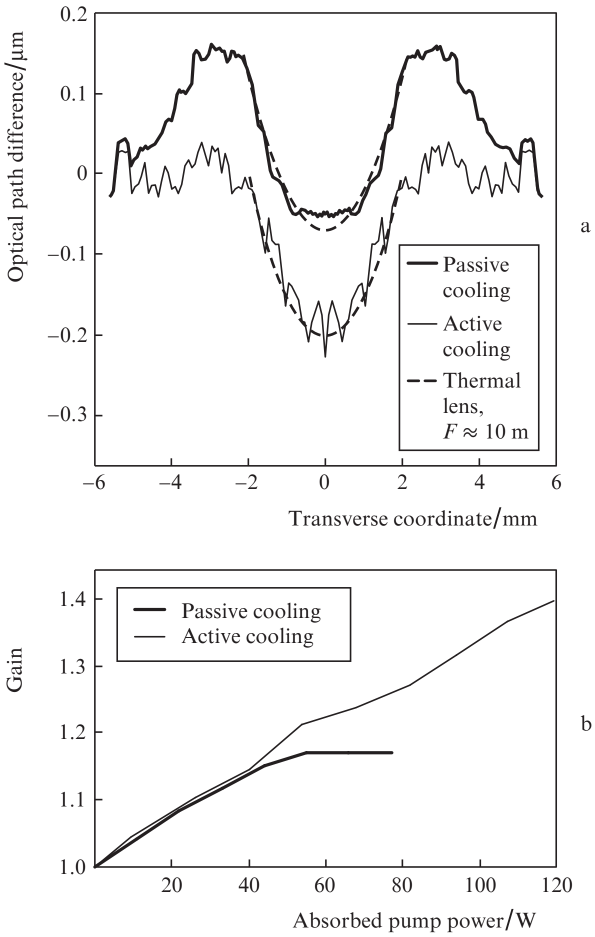

Figure 3. (a) Optical path difference versus the transverse coordinate and (b) small-signal gain coefficient versus the absorbed pump power in the case of active and passive cooling of the active element.

seen from the measurement of the small-signal gain (Fig. 3b). As is seen, the gain in the case of passive cooling is limited by the pump power at which nitrogen begins to boil (thick solid line), while the gain in the case of active cooling continues to increase with increasing pump power (thin solid line).

Successive experiments on amplification in the PA were performed using pumping by fibre-coupled diodes (maximum power 300 W) and composite AEs 15 mm in diameter with different thicknesses and dopant concentrations of 5 at% or 10 at%. To obtain nine V-shape passes through the AE, we used a multipass scheme [13]. Figure 4a shows the dependences of the small-signal gain on the absorbed peak pump power. At a signal pulse repetition rate of 300 Hz, the pump pulse duration was 1 ms, while the repetition rate of 1 kHz corresponded to cw pumping. As is seen from Fig. 4a, the gain is higher in the latter case (Fig. 4a, squares), which is explained by a longer time available for creating the population inversion. As a result, a high (~1000) gain was obtained. This indicates that this scheme can be an alternative to a regenerative amplifier.

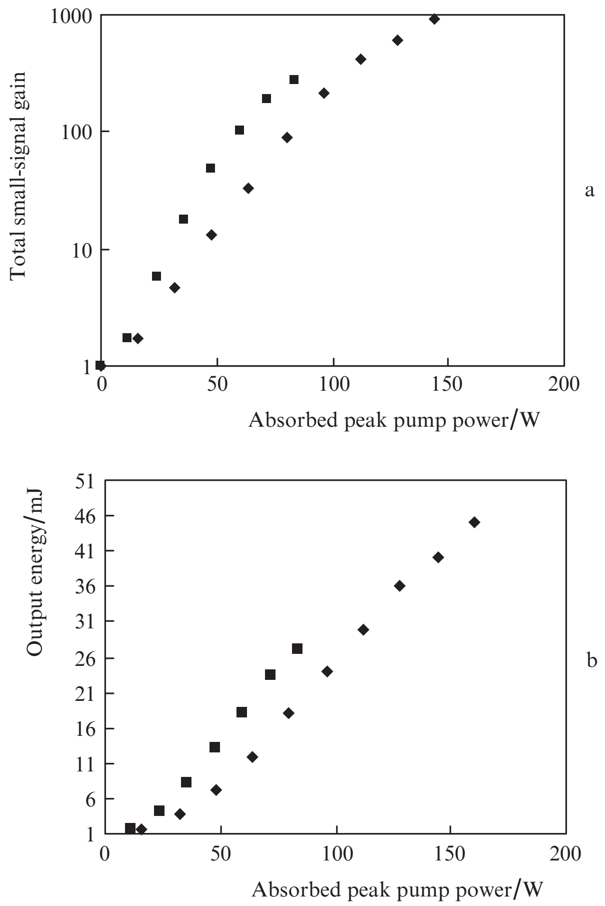

Figure 4. (a) Total small-signal gain and (b) PA output energy vs. the absorbed peak pump power at pulse repetition rates of 300 (◆) and 1000 Hz (■).

In addition, cw pumping provides a higher output energy (Fig. 4b), since the energy accumulation in this case begins not from a zero level, as at a repetition rate of 300 Hz, but from some residual level (the amplified pulse does not take the entire stored energy). As a result, we managed to obtain from the PA and output energy of 47 mJ at a pulse repetition rate of 300 Hz and 27 mJ at a rate of 1 kHz. The variations in the output energy fell within 3%. The efficiency with respect to absorbed pump power was ~33%, which is a rather high value for repetitively pulsed laser systems. Further increase in energy was restricted by breakdown in the case of pulsed pumping and, in the cw pump regime, by instability in the system operation due to vibrations caused by efficient boiling of nitrogen. The PA efficiency can be increased by decreasing the losses on antireflection and reflection coatings. To improve the output beam quality, it is necessary to decrease distortions appeared upon cooling the AE.

3. Main amplifier

The scheme of the main amplifier (MA) is shown in Fig. 5. To obtain a higher gain (and, correspondingly, a higher stored energy), we used two active elements. Similar to the previous cascades, the AEs are Yb:YAG/YAG sandwiches (dopant concentration 10%) 20 mm in diameter, with the Yb:YAG layer 900 μm thick. Each AE was pumped by a fibre-coupled laser diode module with a maximum peak power of 1 kW. Due to a large volume and a large area of vacuum connectors of the MA cryostat, we failed to protect the MA crystals from frosting by creating a deep vacuum as was done in the PA. However, the problem was solved by using a weak flow of gaseous nitrogen inside the chamber. In this case, the requirements to the quality of vacuum seals become much lower.

To amplify a signal with an energy of several tens of millijoules to a signal of several hundreds of millijoules, the MA scheme allows four V-shape passes through each crystal or four W-shape passes through the AEs of the amplifier. The beam emitted from the PA is magnified by a telescope to a diameter of 6 mm, propagates through a polariser, and enters the vacuum chamber through the upper window of the W-pass scheme slightly above the plane of disposition of the AEs, after which it is directed to the first AE and is reflected to the lower mirror of the W-pass scheme and then to the second AE. From this AE, the beam falls to the upper mirror of the periscope and shifts to the lower mirror. Then, the beam passes through the second AE, the upper mirror of the W-pass scheme, the first AE, and exits through the lower window of the W-pass scheme. Here, the beam is reflected back, changes its polarisation, and exits the MA through a polariser. The telescope transfers the image from the periscope back to the periscope retaining a satisfactory beam quality. The pump spot diameter on each crystal is 8 mm.

The dependence of the output energy on the absorbed peak pump power is shown in Fig. 6. The pump pulse duration was 1.2 ms. As a result, we managed to increase the energy of 70-ns pulses from 10 to 120 mJ at a pulse repetition rate of 500 Hz.

The crystals withstood necessary thermal load. However, even insignificant parasitic thermal effects turned out to be quite important. The thermal lens caused a difference in the signal beam diameters on the crystals, while the thermal wedge formed after pump switching on eliminated the coincidence of the centres of the beams of different W-passes. Therefore, to achieve further increase in the output energy, it is necessary to improve the cryostat and use a multipass scheme, which demonstrated good results in the PA. In this case, it will be possible to compensate the thermal lens and, hence, precisely match the pump and signal beam diameters

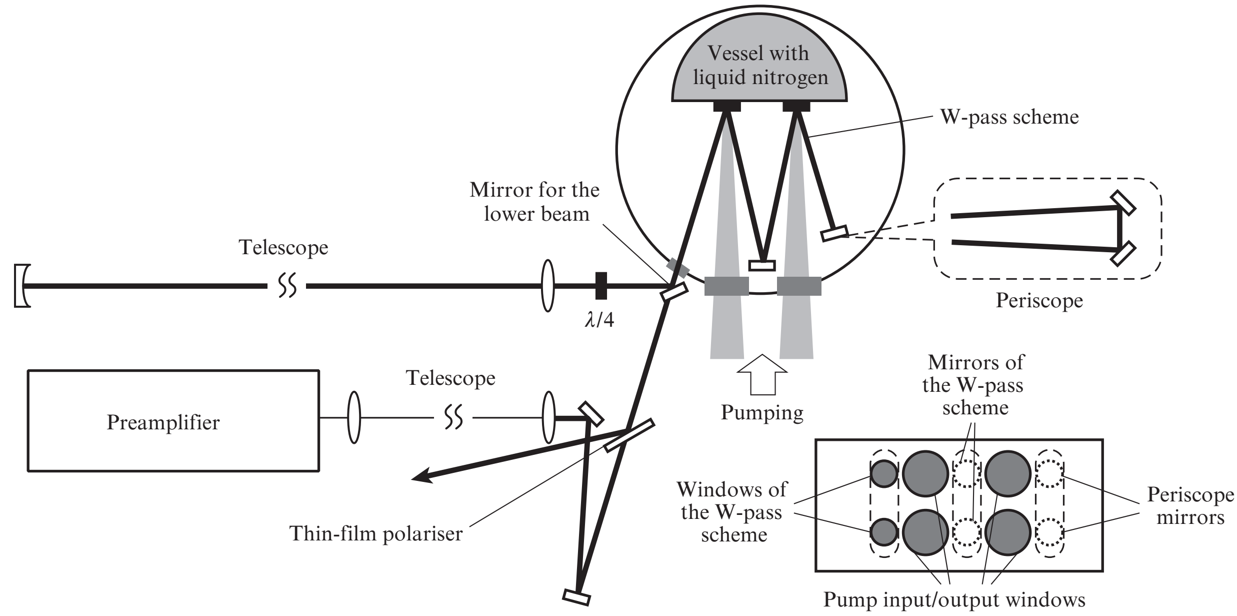

Figure 5. Principal scheme of the main amplifier.

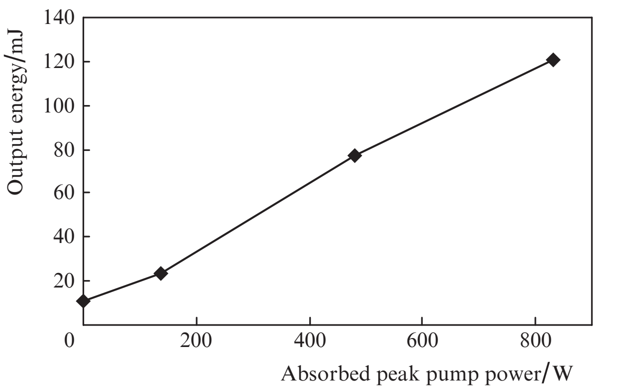

Figure 6. Dependence of the main amplifier output energy on the absorbed peak pump power at a pump pulse duration of 1.2 ms and a repetition rate of 500 Hz.

in each pass through the AEs. It will also be possible to choose the optimal number of passes. The angular deviations of the beam due to the thermal wedge can be easily compensated as well. Based on the results of the PA operation, we can expect that half of energy stored in the AEs of the MA can be extracted, which, according to our calculations, corresponds to 0.5 J at the exit of the MA.

4. Conclusions

A repetitively pulsed laser system is developed based on cryogenically cooled Yb : YAG disks. An original system of active liquid nitrogen cooling was developed and tested, which allowed operation with cw diode pumping. Using our technology of thermal diffusion bonding, we created composite AEs in which the amplified spontaneous emission is much lower. A stable and reliable master-oscillator system with an output energy of 27 mJ, a pulse repetition rate of 1 kHz, and a rather high (~ 33 %) efficiency with respect to absorbed pump power is developed. It is noted that the PA output energy in the case of pulsed pumping with a pulse repetition rate of 300 Hz is lower than in the case of cw pumping. This testifies to a good heat removal from the AEs at cw pumping, otherwise heating would cause a decrease in the gain cross section and, hence, in the energy stored in the crystals. The output laser energy was 120 mJ at a pulse repetition rate of 500 Hz.

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